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Adaptive-SMC based Output Impedance Shaping in DC Microgrids Affected by Inverter Loads

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Abstract—Inverter connected single-phase AC loads cause second-order oscillations in source currents and DC bus voltage. These oscillations degrade the efficiency and reliability of the dc microgrid. In this paper, an adaptive sliding mode control based output impedance shaping (ASMC-OIS) methodology is proposed for voltage regulation, proportional load sharing, and second-order ripple management in a dc microgrid. By using the proposed control method, the magnitude of the output impedance of the source interfacing converter is increased at $2f_{ac}$ programmably, which results in the reduction of second-order ripple currents propagating through the converter. Instead, it is propagated to the dc-link capacitor or towards the nodes which consists of some ripple absorption active or passive filter. This leads to an increase in the energy density of the ripple filters. The dynamic consensus-based secondary control is incorporated to ensure proportional load current sharing. A graph theoretical analysis is presented to analyze per unit load sharing among all the nodes. Stability of the proposed controller is analyzed considering multiple source nodes using Lyapunov's approach. A dc microgrid consisting of parallel-connected dc-dc boost converters, dc load, and inverter load is simulated to verify the proposed control strategy. The proposed ASMC-OIS methodology is validated through experimentation.

Index Terms—Second order ripple reduction, adaptive voltage control, dc microgrid, hybrid microgrid, dynamic droop control, proportional current sharing.

I. INTRODUCTION

A DC microgrid consists of distributed generation units, energy storages, dc and ac loads, interconnected through dc and ac power converters to a common dc bus. In a dc microgrid, proportional load sharing among sources and dc bus voltage regulation is important. When a single-phase AC load is connected to the dc microgrid, the dc bus voltage and source current oscillate at twice the ac supply frequency f_{ac} . The voltage magnitude of the dc bus is tightly controlled to be within the regulation limits. This leads to larger $2f_{ac}$ oscillations in inverter input current than the dc bus voltage. This oscillating input current is called second order ripple currents SRCs. In distributed power generation environment like microgrid, the SRC distribution among sources is affected by the line impedance of the cable connecting the source converter to the dc bus.

The SRCs have various detrimental effects on the power quality, efficiency, and component's reliability. The SRC, when propagates to the PV source, causes a rise in its temperature [1]. The SRCs affect maximum power point tracking (MPPT) mechanism [2]. In the case of wind turbines, SRCs lead to ripple torque in it [3]. In terms of energy storage, batteries

such as Valve Regulated Lead Acid (VRLA), Vented Lead Acid (VLA), Lithium-ion, and Nickel Cadmium (Ni-Cd) are used. All types of batteries heat up when ripple currents are drawn from it. This results in degradation of battery and affects its performance in the long run.

In terms of SRC absorption capacity, different sources and storages have different ability to cater to the ripple current demand. A photovoltaic cell is more affected by the SRCs than the wind turbines as in wind turbines ripple in torque can be reduced using adequate speed control gears [4]. In terms of wind turbines, Vertical Axis Wind Turbines (VAWTs) are more affected than a Horizontal Axis Wind Turbines (HAWTs) [3]. In terms of batteries, Ni-Cd batteries have a relatively lesser rise in temperature compared to the lead-acid batteries when ripple currents are drawn from it [5], [6]. Hence, different sources and storages can be made to share the different magnitude of SRCs. Along with this, in literature, different active and passive filters have been proposed to absorb ripple current [7]. In a microgrid, all source nodes may not consist of such filters, instead, the ripple should be propagated to the nodes having ripple filters. This will reduce the component count and cost of the microgrid.

Several methodologies have been proposed to reduce SRC propagation in two-stage dc-ac inverters in literature. In active control methodologies, linear controllers are used to increase the output impedance at $2f_{ac}$. Based on the virtual impedance based SRC reduction approaches, methods such as Band-pass Filter Inserted Current Feedback Scheme (BPF-ICFS), Notch Filter Inserted Load Current Feedforward Scheme (NF-LCFFS), Notch Filter and Virtual Resistance Load Current Feedforward Scheme (NF+VR-LCFFS) exist as discussed in [8], and references therein. The virtual impedance control methodologies for SRC suppression is proposed in [9]–[11]. In these methods, the inductor current is feedback to the control loop through a bandpass or double bandpass filter to improve dynamics and reduce SRCs. However, such methodologies are good for single converters. The distributed control environment in dc microgrid requires robust controller which is capable of sharing dc load proportionally and reduce or manage SRC at the same time. The dc bus voltage must also be within permissible limits. The ripple sharing technique proposed in [12] shares ripple according to the converter's rated power, however, it may lead to source heating or source failure. An active filter is proposed in [13] to reduce SRCs to PV sources. However, there is an increase in device count, which further increases the cost of the system. It will be beneficial if such

active filters are installed at a node, and SRCs from all other nodes is propagated to this ripple absorbing node which works as a centralized ripple energy storage node as in [14]. This will lead to an increase in the energy density of the active filter. In [15], virtual impedance is introduced using a linear control and ripple is managed according to the state of charge (SoC) of battery. However, the load current is not shared proportionally. In terms of multiple ac loads, the SRCs reflected in the dc side can be reduced by the introduction of adequate phase shift in carriers of the parallel-connected inverters. In [16], authors use phase shifting in carriers to absorb the ripple energy in an extra ripple port, however, such configuration requires extra elements to reduce ripple and for an unknown number of VSCs finding the phase shift angle may not be feasible. In [17] and [18] it is recommended that to operate parallel inverters with reduced ripple, there should be $2\pi/N$ angle between carrier signals for N inverters. Hence, for ripple cancellation with phase shift, the number of inverters must be known beforehand.

This paper proposes a non-linear sliding mode control based SRC sharing methodology, such that along with the dc component of current, the second-order current is also shared. The SRC is shared irrespective of the interfacing converter ratings. By using the proposed ASMC-OIS control, the output impedance of the converter is increased at twice the ac supply frequency as shown in Fig.1. This leads to reduction of ripple current propagating through the converter. Instead it is programmably shared among the nodes having some ripple filtering circuits or to the dc link capacitor. The secondary consensus control is used to incorporate proportional load sharing by dynamic droop control. A sparse communication network is used for per unit load current data exchange between the neighboring control nodes. The communication topology may not be similar to the physical interconnection topology. The salient features of the proposed control are:

- 1) The output impedance of converter is increased at $2f_{ac}$ using ASMC-OIS. The proposed control is robust against modeling uncertainties.
- 2) The proposed controller is fully distributed in nature. The proposed control is capable mitigating the SRC and proportional current sharing is achieved at the same time.
- 3) SRC sharing does not affect proportional dc load sharing among sources. This makes the proposed control applicable to dc and hybrid microgrid.

The paper is organized as follows: Section II consists of the analysis of ripple sharing among converters. Section III consists of an explanation of the proposed control law. The bounds on the controller variables are derived in this section. A small-signal analysis of output impedance shaping is presented in Section IV. In Section V, the stability of the system is analyzed using Lyapunov's approach. The secondary consensus control is presented in Section VI. Sections VII and VIII consists of simulation and experimental verification of the proposed controller, respectively.

II. SECOND ORDER RIPPLE SHARING

The instantaneous output power of a single-phase inverter consists of a constant component P_c and a ripple component P_r . The output power $P_{ac} = V_{ac} I_{ac}$

$$V_{ac}I_{ac} = V_m \cos(\omega t) I_m \cos(\omega t) \quad (1a)$$

On further expanding above equation and dividing power into the constant dc component P_c and ripple component P_r :

$$P_{ac} = \frac{1}{2}V_m I_m + \frac{1}{2}V_m I_m \cos(2\omega t) = P_c + P_r \quad (1b)$$

This ripple power has to be shared by N parallel connected interfacing converters.

$$(P_{c1} + P_{r1}) + \dots + (P_{cn} + P_{rn}) = \frac{1}{2}V_m I_m + \frac{1}{2}V_m I_m \cos(2\omega t) \quad (1c)$$

where, $P_{ci} = V_{dc}I_{ci}$ is constant power component and $P_{ri} = V_{dc}I_{ri}$ is ripple power component supplied by i^{th} converter, where I_{ci} is constant component and I_{ri} is ripple component of load current respectively. By separating the constant and ripple components and substitute $V_m = V_{dc}$ and normalizing by a suitable base current value I_b so as to obtain per unit current $I_{ci}^{pu} = \frac{I_{ci}}{I_b}$, $I_{ri}^{pu} = \frac{I_{ri}}{I_b}$, $I_{mi}^{pu} = \frac{I_{mi}}{I_b}$:

Let

$$\gamma_1 = \frac{I_{r1}^{pu}}{I_m^{pu}} \quad \gamma_2 = \frac{I_{r2}^{pu}}{I_m^{pu}} \quad \dots \quad \gamma_n = \frac{I_{rn}^{pu}}{I_m^{pu}}$$

$$\gamma_1 + \gamma_2 + \dots + \gamma_n = \frac{1}{2} \cos(2\omega t) = \sum_{i=1}^N \gamma_i = \frac{1}{2} \cos(2\omega t) \quad (1d)$$

If the SRC of first converter is controlled, the γ_1 would tend to be 0.

$$\sum_{i=2}^N \gamma_i = \frac{1}{2} \cos(2\omega t) \quad (1e)$$

Hence, all γ_i 's has to increase to satisfy the above equation, and ripple sharing is achieved.

III. PROPOSED CONTROL METHODOLOGY

A decentralized ASMC-OIS methodology is proposed to implement ripple sharing and proportional sharing of dc component of load current. In this, the primary control consists of adaptive sliding mode control (SMC). It is responsible for maintaining a constant dc bus voltage, and ripple control. The ripple is controlled by increasing the output impedance at $2f_{ac}$ frequency. A dynamic consensus-based secondary control adjusts the voltage reference for proportional current sharing among all sources as shown in Fig.3. The per unit load of each converter is communicated to its neighboring converters. The proposed control methodology is explained in the following subsections:

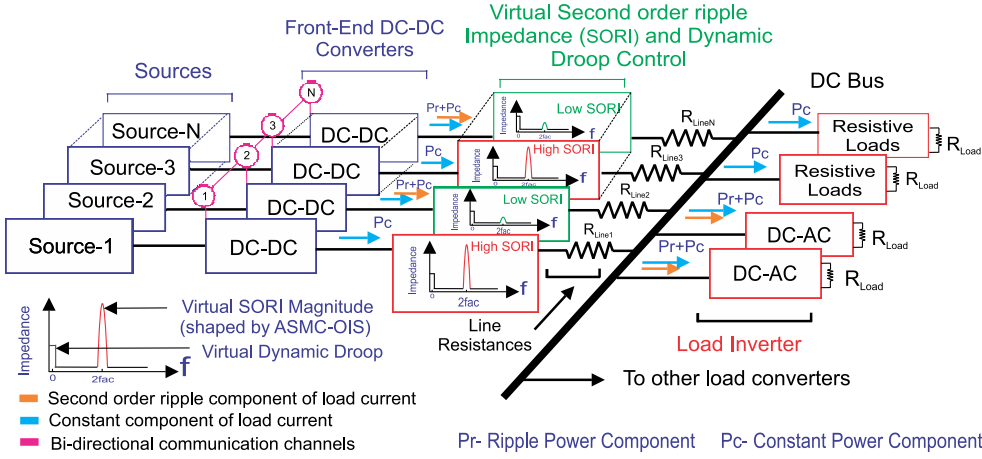


Figure 1: Proposed power sharing scheme: High and low impedance at $2f_{ac}$ is achieved by output impedance shaping

A. Model of i^{th} boost converter in error co-ordinates

The state space average model of i^{th} boost converter connected to a dc bus can be written as:

$$\begin{aligned} L_i \dot{i}_{Li} &= -r_{Li} i_{Li} - (1 - u_i) v_{ci} + V_{dci} \\ C_i \dot{v}_{ci} &= (1 - u_i) i_{Li} - I_{oi} - \sum_{j \in N_i} I_{ij} \end{aligned} \quad (2a)$$

where, L_i , C_i is the inductor and terminal capacitance of i^{th} converter, u_i is the duty cycle, V_{dci} is supply voltage, r_{Li} is inductor resistance. In 2a, substitute the value of $i_{Li} = (e_{ii} + I_i^{ref})$ and $v_{ci} = (e_{vi} + V_i^{ref})$ to obtain the dynamics in error co-ordinates as:

$$\begin{aligned} L_i \dot{e}_{ii} &= -r_{Li} (e_{ii} + I_i^{ref}) - (1 - u_i) (e_{vi} + V_i^{ref}) + V_{dci} \\ C_i \dot{e}_{vi} &= (1 - u_i) (e_{ii} + I_i^{ref}) - I_{oi} - \sum_{j \in N_i} I_{ij} \end{aligned} \quad (2b)$$

where, $e_{vi} = v_{ci} - V_i^{ref}$, $e_{ii} = i_{Li} - I_i^{ref}$, I_{oi} is the output terminal current, V_i^{ref} , and I_i^{ref} are voltage and current references, v_{ci} is output voltage, I_{Li} is inductor current. The equations in error dynamics are used to design the control law. The voltage reference consists of a global desired dc bus value. This reference is common to all converters connected to the dc bus. The voltage reference is changed depending on the desired voltage regulation to implement droop for load sharing.

B. Sliding Mode Control based Adaptive Voltage Control

The primary controller consists of individual sliding mode controllers that receive voltage references from the secondary controller. The switching function is adaptive in nature as in [19]. However, an additional control parameter ρ_i has been used to increase $2f_{ac}$ impedance. The proposed switching function for i^{th} converter is:

$$\begin{aligned} s_i &= \rho_i (i_{Li} - I_i^{ref}) + \alpha_i (v_{ci} - V_i^{ref}) = \rho_i e_{ii} + \alpha_i e_{vi}, \quad (3a) \\ V_i^{ref} &= V_o^{ref} + k_i I_i^{pu} I_r - d_i I_i, \quad \alpha_i = \eta_i (v_{ci} - V_i^{ref})^{\beta_i} \\ d_i &= d_o + g_i \int (I_i^{pu} - I_i^{pu}) \end{aligned}$$

The variables β_i , ρ_i and η_i are positive constants, I_i^{pu} is

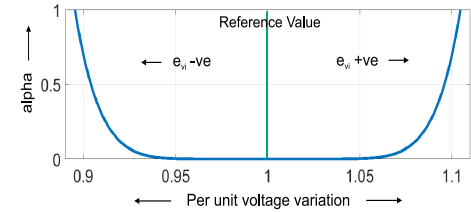


Figure 2: Variation of alpha with voltage error

average microgrid load, I_i is the load current of i^{th} converter and I_r is its current rating. The parameter d_i is dynamic droop, d_o is constant droop and g_i is dynamic droop gain. These are used to control the dynamics of individual converter. The controller is in voltage control mode, when the voltage error finite. When the voltage error becomes negligible, the control shifts to the current regulating mode. The parameter α_i is responsible for maintaining dc bus voltage, while the component ρ_i is used to increase the output impedance. The profile of α variation with respect to the per-unit variation of converter's output voltage with $V^{ref} = 150V$, $\eta=10^{-8}$, $\beta = 6$, and output voltage variation of $\pm 5\%$ of the reference voltage is shown in Fig. 2. The parameter α is designed to be zero when the output voltage is at $\pm 5\%$ of the reference voltage, and finite otherwise. This means that when the voltage is outside the voltage regulation range, the sliding surface primarily consists of voltage error component, while when the voltage error is negligible the surface consist of current error term. In (3a), the constant k_i is a positive constant and its limits are derived as in [20] and d_i is the dynamic droop, derived in Section VI.

C. Control Law

To ensure that the dynamics reach the sliding surface, the time differentiation of sliding surface should be [21]:

$$\dot{s}_i = -\Gamma_i s_i - Q_i \text{sgn}(s_i) \quad \Gamma_i \text{ and } Q_i \in \mathbb{R}^{(+)} \quad (3b)$$

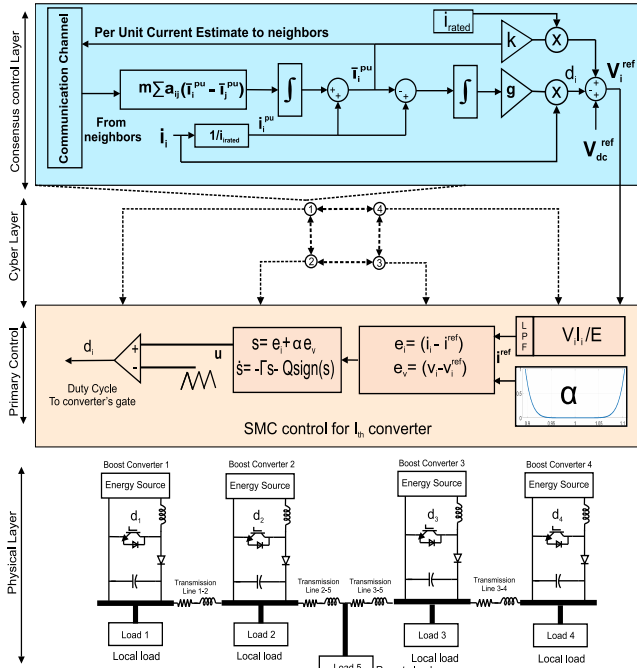


Figure 3: Proposed Control Strategy with Primary and Secondary Control layers

Also, from (3a), the time differentiation of sliding surface is:

$$\dot{s}_i = \rho_i \dot{e}_{ii} + \alpha_i \dot{e}_{vi} + \dot{\alpha}_i e_{vi} = \rho_i \dot{e}_{ii} + \alpha_i (\beta_i + 1) \dot{e}_{vi} \quad (3c)$$

Equate (3b) and (3c) and substitute values from (2b) to solve for the control law,

$$(1-u_i) = \left(\frac{\alpha_i \mu_i (I_{oi} + \sum I_{ij}) + \rho_i r_{Li} (e_{ii} + I_i^{ref}) - \rho_i V_{dci}}{\alpha_i \mu_i (e_{ii} + I_i^{ref}) - \rho_i (e_{vi} + V_i^{ref})} \right) - \left(\frac{L_i (\Gamma_i s_i + Q_i \text{sgn}(s_i))}{\alpha_i \mu_i (e_{ii} + I_i^{ref}) - \rho_i (e_{vi} + V_i^{ref})} \right) \quad (3d)$$

where, $\mu_i = \frac{L_i (\beta_i + 1)}{C_i}$. From (3d) it is observed that branch currents affect the duty value however, branch current is limited by secondary control that maintains a maximum voltage difference between any two nodes i.e. $(V_i - V_j) \leq \varepsilon_{vLim}$.

D. Bounds and selection of the control parameters

For proper operation of controller, the limits of the value of α must be defined. On the sliding surface, $s = 0$ and hence, $e_{ii} = -\frac{\alpha_i}{\rho_i} e_{vi}$. On sliding surface the control law, the second term of (3d) goes to zero.

Substitute, $r_{Li} = 0$ for simplicity. Also, $(I_{oi} + \sum I_{ij}) = \frac{e_{vi} + V_i^{ref}}{Z_o}$. The steady state duty cycle $D_o = (1 - \frac{V_{dci}}{V_i^{ref}}) = (1 - \frac{V_i^{ref}}{Z_o I_i^{ref}})$. Substitute these values in (3d) and divide numerator and denominator by ρ_i :

$$(1-u_i) = \left(\frac{-(\alpha_i/\rho_i) \mu_i (\frac{e_{vi} + V_i^{ref}}{Z_o}) + V_i^{ref} (1-D_o)}{(e_{vi} + V_i^{ref}) + (\alpha_i/\rho_i)^2 \mu_i e_{vi} - (\alpha_i/\rho_i) I_i^{ref}} \right) \quad (4a)$$

Now, club all the known constants to a single one,

$$\kappa_i = (\alpha_i/\rho_i) \quad \lambda_1 = (\kappa_i \mu_i / Z_o) \\ \lambda_2 = (V_i^{ref} - \kappa_i \mu_i I_i^{ref}) \quad \lambda_3 = (1 + \kappa_i^2)$$

Substitute above values to (4a) :

$$(1-u_i) = \left(\frac{(1-D_o) \lambda_2 - \lambda_1 e_{vi}}{\lambda_3 e_{vi} + \lambda_2} \right) \quad (4b)$$

Now, the value of $(1-u_i)$ remains within 0 and 1 i.e. $0 < (1-u_i) < 1$, so the range of κ_i is derived to be:

$$\frac{V_i^{ref}}{I_i^{ref} \mu_i} < \kappa_i < \frac{D_o V_i^{ref}}{\mu_i (D_o I_i^{ref} + \varepsilon_1)} \quad (4c)$$

To select α value, take value of ρ to be unity. Corresponding to this value, the output impedance is maximum. The output impedance is maximum as the current error term e_{ii} in the surface is unity. Corresponding to this value find out the value of α using the bounds defined above. Once α is obtained, the parameter ρ is varied below unity to obtain higher or lower output impedance. When the value of ρ is reduced, the current error term e_{ii} in the surface (3a). Hence, output impedance is regulated.

E. Existence of sliding mode

Existence of sliding mode is guaranteed by η -reachability condition as [21]:

$$s_i \dot{s}_i < \eta |s_i| \quad \eta > 0 \quad (5a)$$

from (3b),

$$s_i \dot{s}_i = s_i (-\Gamma_i s_i - Q_i \text{sgn}(s_i))$$

$$s_i \dot{s}_i = (-\Gamma_i |s_i| - Q_i) |s_i| \quad s_i \text{sgn}(s_i) = |s_i|$$

As, Γ_i and Q_i are both chosen to be negative hence, $(-\Gamma_i |s_i| - Q_i) < \eta$ and hence the reachability condition is satisfied and sliding mode exists. To reduce the effect of chattering, a constant plus proportional rate reaching law 3b is used. Here, the value of Q will regulate the chattering such that lower value of Q will lead to longer reaching time while a higher value of Q leads to severe chattering. Hence, a value of Q is chosen so as to reduce chattering as well as have acceptable reaching time. The parameter Γ is used to add a proportional rate term such that higher the value, faster will be the rate of reaching to the surface [22].

IV. SMALL SIGNAL OUTPUT IMPEDANCE ANALYSIS

The variation of output impedance with control parameters is analyzed by small signal modelling around some operating point. The output impedance analysis presented here is similar to the one proposed in [23]. The small signal averaged model of a converter with state variables at operating point is derived as:

$$x_i = [I_{Li} \quad V_{ci} \quad I_i^{ref}]^T, \quad \dot{I}_i^{ref} = \frac{1}{\tau_i} (I_{Li} - I_i^{ref}) \quad (6a)$$

Consider small perturbations:

$$\hat{x}_i = [\hat{i}_{Li} \quad \hat{v}_{ci} \quad \hat{i}_i^{ref}] \quad (6b)$$

The state space small signal model becomes, To reduce order of system, substitute the equation corresponding to \hat{i}_i^{ref} in terms of other two state variables when $s(\hat{x}) = 0$, i.e.

$$\hat{i}_i^{ref} = \frac{\rho_i \hat{i}_{Li} + \alpha_i \hat{v}_{ci}}{\rho_i} \quad (6c)$$

The reduced small signal model in terms of \hat{i}_{Li} and \hat{v}_{ci} becomes,

$$x_{Ri} = [\hat{i}_{Li} \quad \hat{v}_{ci}] \quad \dot{x}_{Ri} = A_R x_{Ri} + B_R v_{dci} \quad (6d)$$

The output impedance, $\frac{\hat{v}_{ci}}{\hat{i}_{Li}}$ is derived to be,

$$\frac{\hat{v}_{ci}}{\hat{i}_{Li}} = \frac{sL_i}{(1-u_i)^2} + \frac{m_3 m_1}{(1-u_i)(s^2 - m_4 s - m_3 m_2)} \quad (6e)$$

$$m_1 = -m_3, m_2 = \frac{-\alpha_i u_i (\tau_i - C_i R_L + \tau_i (\beta_i + C_i^2 + \beta_i C_i^2))}{K \tau_i}$$

$$m_3 = \frac{-\rho_i u_i^2 R_L}{K}, m_4 = \frac{\rho_i u_i \tau_i C_i^2 - \alpha_i L_i + \rho u_i \tau_i}{K \tau_i}$$

$$K = \alpha_i (L_i + \beta_i L_i) - \rho_i C_i u_i R_L$$

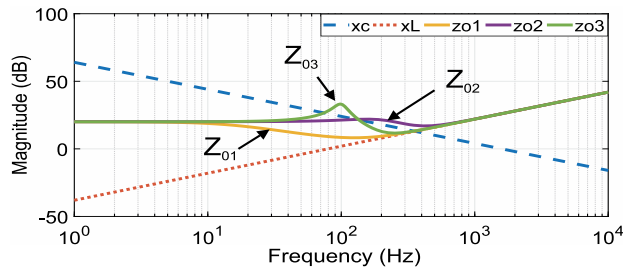


Figure 4: Frequency response of X_c , X_L and Z_o with impedance shaping, $\rho_3 > \rho_2 > \rho_1$ and $Z_{o3} > Z_{o2} > Z_{o1}$, Z_{o1} is impedance without control

The impedance of bus capacitance X_c is higher than the impedance of converter's input inductor X_L at $2f_{ac}$ as shown in Fig.4. Due to this the SRC propagates to the source rather than being absorbed by bus capacitor. To mitigate SRC propagation through the converter, the impedance of inductor is virtually increased at $2f_{ac}$.

V. STABILITY OF PROPOSED CONTROLLER

In this section, the stability of the proposed ASMC-OIS control will be analyzed using Lyapunov approach. Let us choose a Lyapunov function consisting of voltage error e_{vi} . During sliding mode, $s = 0$ or $e_{ii} = -(\alpha_i/\rho_i)e_{vi}$ also, total current output of a converter $I_{oi} = (e_{vi} - V_i^{ref})/Z_i$, where Z_i is the load impedance as seen by i^{th} converter. As output voltage becomes equal to the reference voltage, the e_{vi} converges to zero. The convergence of e_{vi} to zero leads to the convergence of current e_i to zero. The current reference can

further be simplified as $I_i^{ref} = V_i^{ref}/(Z_i(1 - D_{oi}))$, where duty cycle $D_{oi} = 1 - (V_{dci}/V_i^{ref})$, also $u_i = 1 - (V_{dci}/V_i)$. Consider the following Lyapunov function for N converter system as shown in Fig. 5 :

$$V = \frac{e_{v1}^2}{2} + \frac{e_{v2}^2}{2} + \frac{e_{v3}^2}{2} + \dots + \frac{e_{vn}^2}{2} \quad (7a)$$

differentiate above equation with respect to time,

$$\dot{V} = \dot{e}_{v1}e_{v1} + \dot{e}_{v2}e_{v2} + \dots + \dot{e}_{vn}e_{vn} \quad (7b)$$

For stability $\dot{V} < 0$.

$$\dot{V} = \dot{V}_1 + \dot{V}_2 + \dots + \dot{V}_n \quad (7c)$$

where, V_i is Lyapunov function for i^{th} node such that $i=1,2,\dots,n$.

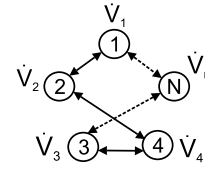


Figure 5: Stability analysis of voltage variation at N converter nodes

On substituting the value of e_{vi} and \dot{e}_{vi} from (2b) , the value of Lyapunov function \dot{V}_n at n^{th} node becomes:

$$\dot{V}_n = \dot{V}_a + \dot{V}_b \quad (7d)$$

$$\dot{V}_a = \frac{-e_{vn}^2}{C_n} \left((1 - u_n)\alpha_n + \frac{1}{Z_{on}} \right) - e_{vn} \frac{V_n^{ref}}{Z_{on}} \left(1 - \frac{(1 - u_n)}{(1 - D_{on})} \right) \quad (7e)$$

$$\dot{V}_b = -e_{vn} \sum_{j \in N_1} I_{1n} \quad (7f)$$

1) *Negative definite V_a* : In this section V_a is proved to be negative definite. The first term of V_a is negative definite as the value of $(1 - u_n)$ remains within zero and one. Also, C_n and Z_{on} are positive constants. The control variable for dc bus control is also a positive constant. The next term of V_a consists of ratio $(1 - u_n)$ and $(1 - D_{on})$. In case of some voltage error e_{vn} , $(1 - u_n) > (1 - D_{on})$ for $e_{vn} > 0$, and $(1 - u_n) < (1 - D_{on})$ for $e_{vn} < 0$. This makes the second term negative denite [19]. Hence, overall V_a will always be negative definite.

2) *Negative definite V_b* : The V_b term in above equations depends on the branch circulating current among converters.

$$\dot{V}_b = -e_{v1} \sum_{j \in N_1} I_{1j} - e_{v2} \sum_{j \in N_2} I_{2j} \dots - e_{vn} \sum_{j \in N_n} I_{nj} \quad (7g)$$

The branch current between i^{th} and j^{th} node will be :

$$I_{ij} = \frac{V_i - V_j}{r_{ij}} = \frac{\epsilon_{vLim}}{r_{ij}}$$

where, ϵ_{vLim} is the maximum voltage difference between any two nodes.

$$\dot{V}_b = - \sum_{n=1}^N \left(\sum_{m=1, m \neq n}^N e_{vn} \left(\frac{V_n - V_m}{r_{nm}} \right) \right) \quad (7h)$$

for simplicity consider all line resistance between two nodes be r . The mean of all the node voltages will be (or the voltage at the dc bus is) :

$$\bar{V} = \frac{(V_1 + \dots + V_n)}{N} = \sum_{i=1, i \neq j}^N V_i = N\bar{V} - V_j; \quad j = 1..n \quad (7i)$$

Substitute in (7h)

$$\dot{V}_b = - \sum_{n=1}^N e_{vn} \left(\frac{(N-1)V_n - (N)\bar{V}}{r} \right) \quad (7j)$$

The maximum allowable deviation is ϵ_{vLim} as discussed earlier. This voltage deviation varies as the voltage error varies, as the voltage reference to each converter is the desired dc bus voltage which is \bar{V} . Hence, (7j) reduces to,

$$\dot{V}_b = - \sum_{n=1}^N e_{vn} \left(\frac{e_{vn}}{r} \right) \quad (7k)$$

Hence, \dot{V}_b is negative definite. Also, V_a has been proved to be negative definite. As a result of this, $\sum_{i=1}^N \dot{V}$ in (7c) is negative definite. Hence, the proposed control methodology is stable. The proposed control methodology is shown in Fig. 3. Futhur in multi-agent sense the stability can be analyzed as in [24]. The overall microgrid system and the sliding surface can be written as:

$$L\dot{I}_L = -R_L I_L - U.V_c + V_{dc} \quad (7l)$$

$$C\dot{V}_c = U.I_L - GZ^{-1}G^T V_c - I_{Ld}$$

$$S = \rho(I_L - I_{ref}) + \alpha(V_c - V_{ref}) \quad (7m)$$

where, inductor current $I_L = [i_{L1}, \dots, i_{Ln}]^T$, terminal voltage $V_c = [v_{c1}, \dots, v_{cn}]^T$, inductor resistance $R_L = \text{diag}[r_{L1}, \dots, r_{Ln}]$, inductance $L = \text{diag}[L_1, \dots, L_n]$, capacitance $C = \text{diag}[C_1, \dots, C_n]$, $V_{dc} = [v_{dc1}, \dots, v_{dc2}]^T$, control law $U = [(1 - u_1), \dots, (1 - u_n)]^T$, control parameter $\rho = \text{diag}[\rho_1, \dots, \rho_n]$, load current $I_{Ld} = \text{diag}[i_{Ld1}, \dots, i_{Ldn}]$, load impedance $Z = \text{diag}[z_{o1}, \dots, z_{on}]$, reference current $I_{ref} = \text{diag}[i_{ref1}, \dots, i_{refn}]$, reference voltage $V_{ref} = \text{diag}[v_{ref1}, \dots, v_{refn}]$, $\alpha = \text{diag}[\alpha_1, \dots, \alpha_n]$ and G is the incidence matrix of network topology. Linearize (7l) around (I_{ref}, V_{ref}) ,

$$L\dot{I}_L = -R_L(I_L - I_{ref}) - (U - U_{ref}).V_c + U_{ref}(V_c - V_{ref}) \quad (7n)$$

$$C\dot{V}_c = (U - U_{ref}).I_{ref} + U_{ref}(I_L - I_{ref}) - GZ^{-1}G^T(V_c - V_{ref})$$

When the dynamics are on sliding surface then, $S=0$ and $\dot{S}=0$, which implies that,

$$\rho(I_L - I_{ref}) + \alpha(V_c - V_{ref}) = 0 \quad (7o)$$

$$\rho(\dot{I}_L) + \alpha(\beta + 1)(\dot{V}_c) = 0 \quad (7p)$$

Substitute values from (7n) to (7p) and simplify to obtain U as,

$$U = U_{ref} + M_1^{-1} \left((C^{-1}\alpha(\beta + 1)(U_{ref}.\hat{I}_L + GZ^{-1}G^T\hat{V}_c) - L^{-1}\rho(R_L\hat{I}_L + U_{ref}.\hat{V}_c) \right) \quad (7q)$$

where, $M_1 = (V_{ref}L^{-1}\rho - C^{-1}\alpha(\beta + 1)I_{ref})^{-1}$

In above equation, $\hat{I}_L = (I_L - I_{ref})$, $\hat{V}_c = (V_c - V_{ref})$. The U obtained in (7q) is the equivalent control matrix. Now, substitute the value of U from (7q) to (7l), and use (7o) to reduce the order of system and simplify,

$$C\dot{\hat{V}}_c = \left(U_{ref}.\alpha\rho^{-1}(1_n + C^{-1}\alpha(\beta + 1)) - I_{ref}M_1^{-1}L^{-1} \right. \\ \left. (R_L\alpha + U_{ref}.\rho) + GZ^{-1}G^T(C^{-1}\alpha(\beta + 1) - 1_n) \right) \hat{V}_c = M\hat{V}_c \quad (7r)$$

Now, let the Lyapunov function be $V = \hat{V}_c^T \hat{V}_c$, for stability, $\dot{V} < 0$, hence, $\hat{V}_c^T \dot{\hat{V}}_c + \hat{V}_c^T \hat{V}_c < 0$. Hence, to ensure stability, the matrix M must be designed to be sufficiently negative so as to ensure $M + M^T < 0$ [24].

VI. PROPORTIONAL CURRENT SHARING

A DC microgrid is usually designed so that the sources share load in proportional to their rating [25]. In this section, a distributed consensus based control is proposed by means of which the converters at different nodes communicate their per unit load current values with their neighbors to reach consensus in per unit load sharing.

A. Dynamic consensus control

To estimate average current for j^{th} converter :

$$\bar{I}_j^{pu} = I_j^{pu} + \int \sum_{i=1}^N m a_{ij} (\bar{I}_i^{pu} - \bar{I}_j^{pu}) \quad (8a)$$

where, a_{ij} is an element of adjacency matrix of the communication topology and m is a positive constant, \bar{I}_j^{pu} is the per unit microgrid loading estimated by j^{th} converter, I_j^{pu} is the per unit load of j^{th} converter, \bar{I}_i^{pu} is the per unit microgrid loading estimated by neighbors of i^{th} converter. Due to dynamic consensus, steady state value of per unit current estimated of by all converters should be the same. Let \mathcal{L} represent the Laplacian matrix of balanced communication graph, the steady state value is

$$\bar{I}^{pu}(s) = s(s1_n + m\mathcal{L})^{-1}(I_c^{pu}(s)) \quad (8b)$$

$$\bar{I}_{ss}^{pu} = \frac{1}{N} [1_N, 1_N, \dots, 1_N] (I_{css}^{pu}) \quad (8c)$$

Where 1_N is a $1 \times N$ unit matrix. Steady state value would consist of sum of averaged constant dc term I_{css}^{pu} [26]. Hence, steady state current reference would reach consensus for all converters.

B. Dynamic droop control

Dynamic droop control is implemented for proportional current sharing. The value of droop constant is calculated by :

$$d_i = d_o + g_i \int (I_i^{pu} - I_i^{\bar{pu}}) \quad (9a)$$

where g_i is a positive constant and d_o is the initial droop constant. I_i^{pu} is inductor current of the dc-dc converter and $I_i^{\bar{pu}}$ is the reference current estimated by the converter by consensus control. The global local voltage reference is adjusted as in [20]. The voltage reference is obtained by reducing the actual reference by output current times the droop calculated in (9a).

VII. SIMULATION RESULTS

A dc microgrid consisting of three parallel connected boost converter is simulated. A resistive load and an inverter load is connected to the dc bus. The parameters of converters and loads used for simulation is given in Table I. A balanced communication graph is chosen so as to facilitate the nodes to exchange per unit load current value with its neighboring nodes. The simulation plots with dc and ac load loading is shown in Fig.6a. The proposed controller was disabled during time interval t_1 . Due to unequal line resistances, different sources are loaded differently. During the time interval t_2 , the dynamic droop control is enabled. In this time interval, a constant resistance load is applied on the dc microgrid. As a result, all sources share equal current as shown in Fig. 6a. During the time interval t_3 , the inverter load is turned on. Due to ac load, the SRC can be seen.

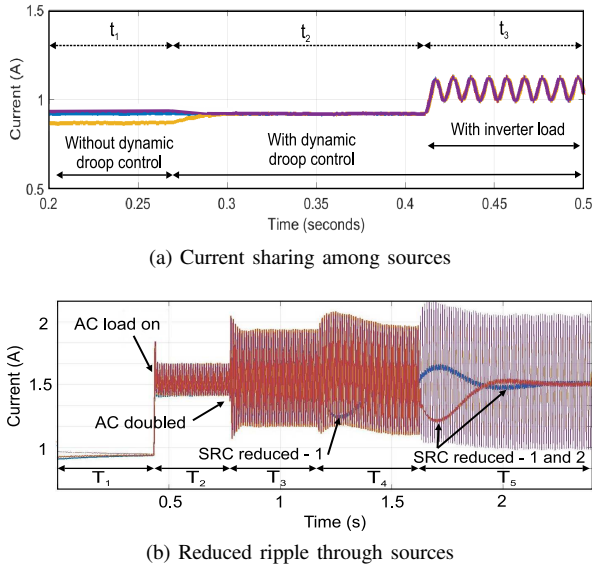


Figure 6: Simulated source current waveform

Once the inverter load is applied the parameter ρ_i is adjusted to reduce the SRC passing through the converter by increasing the output impedance at $2f_{ac}$ frequency, when $\rho_i = 1$, the SRC propagating through it is minimum, as shown in Fig.6b. Initially, ρ for all converters is 0.2. Hence, all sources share equal ripple during T_2 in Fig. 6b. The ac load is doubled during T_3 . This leads to an increase in SRCs. During T_4 , the

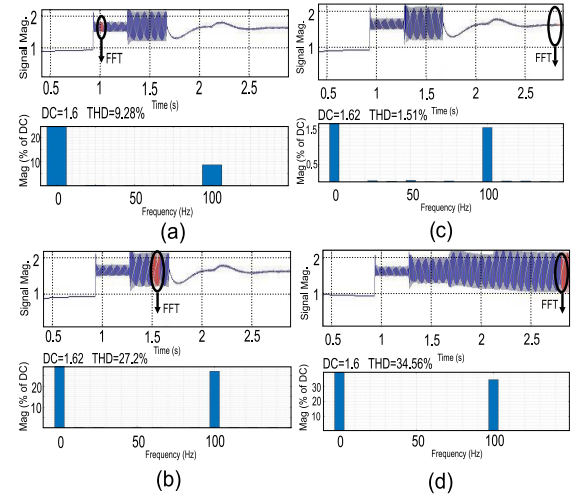


Figure 7: FFT analysis of current- (a) Converter 1 (b) Converter 1 when ac load is doubled (c) Converter 1 after ASMCOIS is implemented (SRC mitigated) (d) Converter 3 (increased SRC due to low output impedance)

ρ_1 is increased. This increases the impedance of converter-1. The SRC reduction can be seen in T_4 . Similarly, during T_5 , impedance of converter -2 is also increased. The reduced SRCs can be observed in converter 1 and 2. The SRC through converter 3 increases due to low value of impedance. Hence, SRC sharing is achieved. The dc value of load current remains the same. The FFT analysis of current waveform of converter-1 and 3 during different stages is shown in Fig. 7. The FFT of converter 1 during T_2 and T_3 and T_5 of Fig. 6b is shown in Fig.7a, Fig.7b and Fig.7c respectively. It can be observed that the THD increases from 9.28% to 27.2% due to increase in ac load. Further, THD reduces to 1.51% when the control is implemented. Hence, SRC is reduced significantly. On the other hand, FFT of converter 3 during interval T_5 of Fig. 6b is shown in Fig.7d. The THD increases to 34.56% as the SRC now propagates through converter 3.

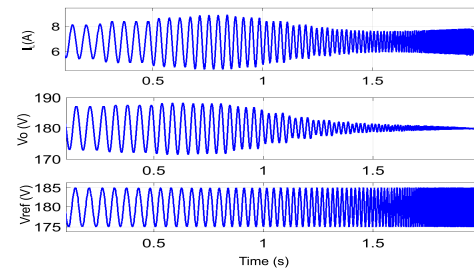


Figure 8: The output impedance estimation using frequency sweep (10 to 10^4 Hz)

Further, the effect of variation of ρ on output impedance is analysed by frequency sweep from 10 to 10^4 Hz. The voltage and current waveform obtained from frequency sweep is shown in Fig. 8. It can be seen that the magnitude diminishes as frequency increases. The frequency response of \hat{v}_c/\hat{i}_L for different ρ value is shown in Fig. 9. In Fig. 9, the dots represent the impedance obtained from frequency sweep, and

the solid line is the frequency response of estimated transfer function with best fit. It can be observed that the impedance with $\rho=1$ is 30 dB more compared to dc bus capacitance. Hence, output impedance is increased and SRC propagates to the bus capacitor. On the other hand, when $\rho=0.1$, the impedance is 5dB less than the dc bus capacitance. Hence, the SRC propagates to the source through the converter due to lower impedance path. Hence, the proposed control is verified to reduce SRC.

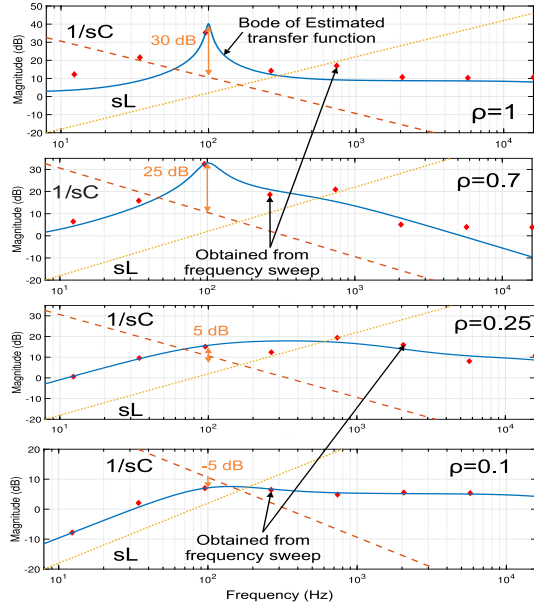


Figure 9: Frequency response of \hat{v}_c/\hat{i}_L obtained from frequency sweep to verify effect of ρ on impedance at 100 Hz

VIII. EXPERIMENTAL RESULTS

The proposed control law is validated by experimentation on a 1.5kW laboratory setup shown in Fig.10. Three boost converters were connected in parallel to form a dc microgrid. Three regulated power supplies with maximum rating of 50V, 10A were connected as power source to the converters. The control algorithm is implemented on Opal-RT Real Time Digital Simulator. The individual control signal is given from Opal-RT to the three parallel connected boost converter setup. An open loop SPWM inverter and a resistance is connected to dc bus as load. The parameters for each converter is given in Table I. The communication routine for data exchange between nodes is implemented on Matlab. The delay in communication has not been addresses in present work, however methods proposed in [27] and references therein can be used.

The parameters for designing α , i.e. η, β are same for all three converters. The adjacency \mathcal{A} , in-degree \mathcal{D} , and Laplacian matrix \mathcal{L} for communication topology is:

$$\mathcal{A} = \begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix} \quad \mathcal{B} = \begin{bmatrix} 2 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 2 \end{bmatrix} \quad \mathcal{L} = \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}$$

A. DC component sharing

Three equally rated boost converters are connected in parallel and controlled using the proposed method so as to have dc

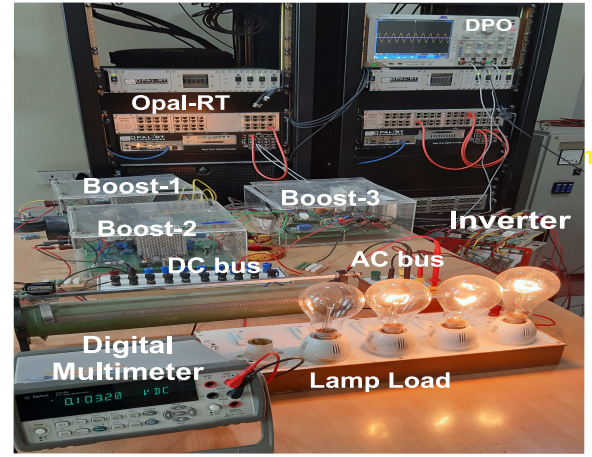
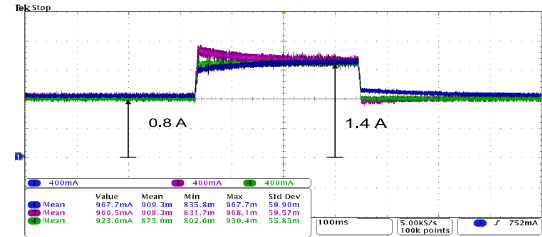
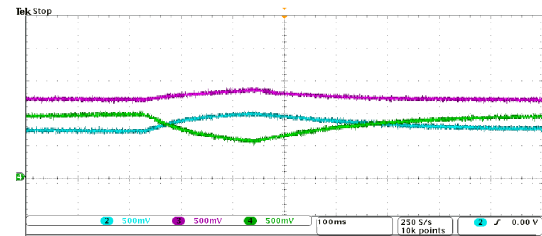


Figure 10: Experimental setup

bus voltage of $140 \pm 5\%$ V. DC load is increased from 400 W to 600 W and then back to 400 W. Equal load sharing is observed from Fig. 11a. The figure shows the output current of parallel connected converters. Dynamic variation of droop is shown in Fig.11b.



(a) Equal load current sharing among converters



(b) Dynamic variation in droop during load changes

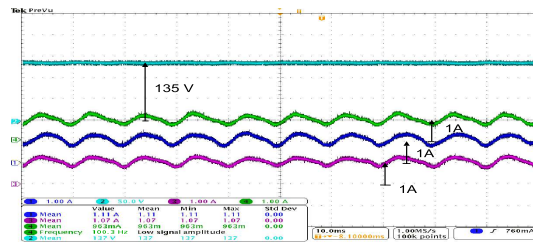
Figure 11: DC and voltage reference variation due to dc load changes

B. Equal second order ripple sharing

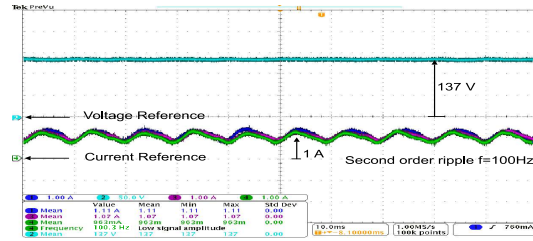
The inverter fed resistance load of 300 W is connected to the dc bus, along with a resistance load of 120 W. The maximum voltage at inverter output terminals is 110V. Initially, ρ_1, ρ_2, ρ_3 are equal to 0.2. Due to equal value of control parameter ρ , the output impedance at $2f_{ac}$ of all the converters is same. Hence, they share equal ripple as shown in Fig. 12a and dc component of load is shared proportionally as shown in Fig. 12b.

Table I: Simulation and Experimental parameters

Parameters	Conv. 1	Conv. 2	Conv. 3
DC source voltage (V)	50	50	50
L (mH)	2	2.2	2.4
C (μ F)	100	200	100
β	6	6	6
η	1×10^{-8}	1×10^{-8}	1×10^{-8}
$R_{line} (\Omega)$	1	1.5	2
$d_o (\Omega)$	1	1	1
$k (\Omega)$	0.8	0.8	0.8
m, g	50, 0.1	50, 0.1	50, 0.1
Switching Frequency (KHz)	20	20	20
Converter input voltage	50	50	50
LPF time constant τ	0.5 ms		
$\Gamma_i, Q_i, (i = 1 - 3)$	170000, 2000		
Inverter Switching Frequency	5 KHz		
Resistive load (Ω)	100		
Inverter fed load	4x100W bulbs		



(a) SRC when inverter is turned on



(b) Equal dc component sharing among sources

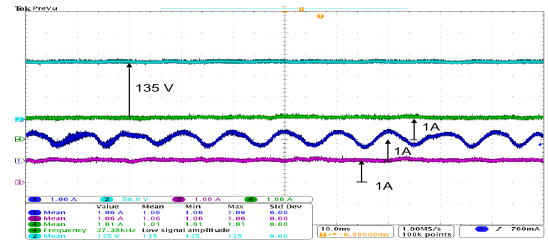
Figure 12: SRC due to dc and ac load

C. Ripple reduction through Converter-1 and 3

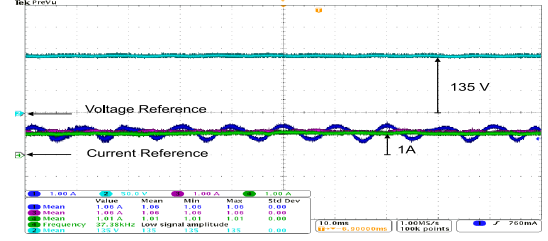
In this section, the ripple is now made to propagate only through converter-2. The ripple control parameter of converters are: $\rho_1 = 0.7$, $\rho_3 = 0.7$ while $\rho_2 = 0.1$. Due to low value of ρ_2 , the SRCs primarily propagate through this converter, as shown in Fig. 13a. Although the SRCs through converter-2 is increased, this converter still supplies the proportional dc component of load current as shown in Fig. 13b. The dc bus voltage also remains constant.

Table II: Comparison

Parameters	[12]	[15]	Proposed
Type of Controller	PI	PI	SMC
Type of droop	Constant	Constant	Dynamic
SRC sharing dependence on converter rating	Depends	Depends	Does not depend
Proportional load sharing	No	No	Yes
DC component sharing	Yes	No	Yes



(a) Reduced ripple propagating through converter 1 and 3



(b) Proportional dc component sharing

Figure 13: DC and ripple component sharing

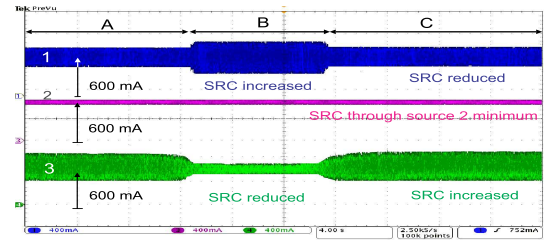


Figure 14: Ripple component sharing among converters

D. Ripple sharing among nodes

In this section, ripple sharing among converters shown in Fig.14, with changes in ρ is explained. The parallel connected converters have the same α_i and different values of ρ_i . During section A, the impedance of converter 2 is more than converters 1 and 3. As a result, SRC in converter 3 is more than SRC in other converters. In section B, the ρ_2 is kept same while that of ρ_1 is made less than ρ_3 . As a result, the SRC in converter 1 increases and becomes more than converter 3, and SRC reduces in converter 3. During section C, the ρ_1 and ρ_3 is made same as in section A. The SRC distribution becomes same as in section A. Hence, the SRC sharing is achieved. The dc load current value remains same in all the sections while SRC is shared. Hence, the proposed control is verified through experiments. Comparison of proposed methodology with other methods is given in Table II.

IX. CONCLUSION

The paper has proposed a solution to share or reduce SRCs while maintaining good voltage regulation and proportional load sharing among sources and energy storages. The proposed ASMC-OIS methodology reduces second order ripple propagating through a converter by increasing the converter's output impedance at $2f_{ac}$. From experimentation it has been verified that the dynamic parameter α maintains the dc bus voltage within $\pm 5\%$ of rated voltage. The ripple reduction

has been achieved, such that for increase of ρ from 0.2 to 1, the SRC gets reduced from 0.4A to 0.1A for 1A dc component. Hence, ρ has been increased or decreased to adjust the output impedance and regulate ripple propagation at different nodes. Using the proposed controller, the SRC is propagated to nodes having higher capacitance or ripple absorption ports. This will improve the energy density in ripple absorption circuits and improve the overall efficiency of the microgrid. As the ripple is propagated to nodes having ripple filters, a smaller capacitance can be used in the active filtering circuits. This allows the usage of non-electrolytic capacitors which have higher life time compared to the electrolytic ones. By using the proposed controller, the dc component is shared proportionally even in the absence of any inverter load. Hence, the proposed controller has been verified for DC microgrid with only dc loads or dc and inverter fed ac loads. The proposed controller has been validated using simulation and experimentation.

REFERENCES

- [1] W. Kim, V.-H. Duong, T. Tuan, and W. Choi, "Analysis of the effects of inverter ripple current on a photovoltaic power system by using an ac impedance model of the solar cell," *Renewable Energy*, vol. 59, pp. 150–157, 11 2013.
- [2] Y. Liu, B. Ge, H. Abu-Rub, and D. Sun, "Comprehensive modeling of single-phase quasi-z-source photovoltaic inverter to investigate low-frequency voltage and current ripple," *2014 IEEE Energy Conversion Congress and Exposition (ECCE)*, pp. 4226–4231, 2014.
- [3] Y. Y. Xia, J. E. Fletcher, S. J. Finney, K. H. Ahmed, and B. W. Williams, "Torque ripple analysis and reduction for wind energy conversion systems using uncontrolled rectifier and boost converter," *IET Renewable Power Generation*, vol. 5, no. 5, pp. 377–386, Sep. 2011.
- [4] M. A. Parker, C. Soraghan, and A. Giles, "Comparison of power electronics lifetime between vertical- and horizontal-axis wind turbines," *IET Renewable Power Generation*, vol. 10, no. 5, pp. 679–686, 2016.
- [5] "Ieee draft recommended practice for sizing lead-acid batteries for stationary applications," *IEEE P485/D2, October 2016*, pp. 1–67, Jan 2016.
- [6] "Ieee guide for batteries for uninterruptible power supply systems," *IEEE Std 1184-2006*, pp. 1–63, 2006.
- [7] M. A. Vitorino, L. F. S. Alves, R. Wang, and M. B. de Rossiter Corrêa, "Low-frequency power decoupling in single-phase applications: A comprehensive overview," *IEEE Transactions on Power Electronics*, vol. 32, no. 4, pp. 2892–2912, April 2017.
- [8] L. Zhang, X. Ruan, and X. Ren, "Second-harmonic current reduction for two-stage inverter with boost-derived front-end converter: Control schemes and design considerations," *IEEE Transactions on Power Electronics*, vol. 33, pp. 6361–6378, 2018.
- [9] L. Yang, Y. Chen, A. Luo, W. Wu, K. Huai, X. Zhou, L. Zhou, Q. Xu, and J. M. Guerrero, "Second ripple current suppression by two bandpass filters and current sharing method for energy storage converters in dc microgrid," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 5, no. 3, pp. 1031–1044, Sep. 2017.
- [10] L. Zhang, X. Ren, and X. Ruan, "A bandpass filter incorporated into the inductor current feedback path for improving dynamic performance of the front-end dc–dc converter in two-stage inverter," *IEEE Transactions on Industrial Electronics*, vol. 61, no. 5, pp. 2316–2325, May 2014.
- [11] G. Zhu, X. Ruan, L. Zhang, and X. Wang, "On the reduction of second harmonic current and improvement of dynamic response for two-stage single-phase inverter," *IEEE Transactions on Power Electronics*, vol. 30, no. 2, pp. 1028–1041, Feb 2015.
- [12] M. Hamzeh, A. Ghazanfari, Y. A. I. Mohamed, and Y. Karimi, "Modeling and design of an oscillatory current-sharing control strategy in dc microgrids," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 11, pp. 6647–6657, Nov 2015.
- [13] A. C. Kyritsis, N. P. Papanikolaou, and E. C. Tatakis, "Enhanced current pulsation smoothing parallel active filter for single stage grid-connected ac-pv modules," in *2008 13th International Power Electronics and Motion Control Conference*, Sep. 2008, pp. 1287–1292.
- [14] X. Shen, M. Shahidehpour, Y. Han, S. Zhu, and J. Zheng, "Expansion planning of active distribution networks with centralized and distributed energy storage systems," *IEEE Transactions on Sustainable Energy*, vol. 8, no. 1, pp. 126–134, Jan 2017.
- [15] L. Jia, C. Du, C. Zhang, and A. Chen, "An esu soc balancing control method with output current ripple suppression ability in dc microgrid," in *2017 36th Chinese Control Conference (CCC)*, July 2017, pp. 9091–9095.
- [16] P. T. Krein, R. S. Balog, and M. Mirjafari, "Minimum energy and capacitance requirements for single-phase inverters and rectifiers using a ripple port," *IEEE Transactions on Power Electronics*, vol. 27, no. 11, pp. 4690–4698, Nov 2012.
- [17] J. S. Siva Prasad and G. Narayanan, "Minimization of grid current distortion in parallel-connected converters through carrier interleaving," *IEEE Transactions on Industrial Electronics*, vol. 61, no. 1, pp. 76–91, Jan 2014.
- [18] D. Zhang, F. Wang, R. Burgos, R. Lai, and D. Boroyevich, "Dc-link ripple current reduction for paralleled three-phase voltage-source converters with interleaving," *IEEE Transactions on Power Electronics*, vol. 26, no. 6, pp. 1741–1753, June 2011.
- [19] A. R. Gautam, K. Gourav, J. M. Guerrero, and D. M. Fulwani, "Ripple mitigation with improved line-load transients response in a two-stage dc–dc–ac converter: Adaptive smc approach," *IEEE Transactions on Industrial Electronics*, vol. 65, pp. 3125–3135, 2018.
- [20] S. Anand, B. G. Fernandes, and J. Guerrero, "Distributed control to ensure proportional load sharing and improve voltage regulation in low-voltage dc microgrids," *IEEE Transactions on Power Electronics*, vol. 28, no. 4, pp. 1900–1913, April 2013.
- [21] C. Edwards and S. Spurgeon, *Sliding Mode Control: Theory and Applications*. Boca Raton, FL, USA: CRC, 1998.
- [22] J. Y. Hung, W. Gao, and J. C. Hung, "Variable structure control: a survey," *IEEE Transactions on Industrial Electronics*, vol. 40, no. 1, pp. 2–22, Feb 1993.
- [23] P. Mattavelli, L. Rossetto, and G. Spiazzi, "Small-signal analysis of dc–dc converters with sliding mode control," *IEEE Transactions on Power Electronics*, vol. 12, no. 1, pp. 96–102, Jan 1997.
- [24] M. Cucuzzella, R. Lazzari, S. Trip, S. Rosti, C. Sandroni, and A. Ferrara, "Sliding mode voltage control of boost converters in dc microgrids," 2018.
- [25] S. Augustine, M. K. Mishra, and N. Lakshminarasamma, "Adaptive droop control strategy for load sharing and circulating current minimization in low-voltage standalone dc microgrid," *IEEE Transactions on Sustainable Energy*, vol. 6, no. 1, pp. 132–141, Jan 2015.
- [26] R. Olfati-Saber and R. M. Murray, "Consensus problems in networks of agents with switching topology and time-delays," *IEEE Transactions on Automatic Control*, vol. 49, pp. 1520–1533, 2004.
- [27] R. Zhang and B. Hredzak, "Distributed finite-time multiagent control for dc microgrids with time delays," *IEEE Transactions on Smart Grid*, vol. 10, no. 3, pp. 2692–2701, May 2019.